Will McKinzie
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ATLANTIC AEROSPACE ELECTRONICS CORPORATION

proposal for

ARCHES: Antennas in Reconfigurable High Impedance Electromagnetic Surfaces

submitted to

DARPA/ETO

for

BAA 99-19
RECONFIGURABLE APERTURE
(ADDRESSING TECHNICAL AREAS I-IV)

submitted by

Atlantic Aerospace Electronics Corporation
(Other Small Business)
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Team Member: Arizona State University (Other Educational)

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Total Funds Requested: $2,539,499

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[redacted]

DARPA/ETO
3701 North Fairfax Drive
Arlington, VA2203-1714

Attn: BAA 99-19

Dear Sir or Madam:

Atlantic Aerospace is pleased to submit a two-volume proposal in response to BAA 99-19. We request a Cost Plus Fixed Fee (CPFF) –type of award and have costed our proposal accordingly. The period of performance requested is for 26 months, beginning 1 October 99. Atlantic's Fiscal Year runs from 1 July through 30 June.

Since Atlantic will be subject to FAR Subpart 15.401, cost and pricing data has been included in our package in order to perform a reasonable cost analysis. If anything is missing, we will gladly provide the documentation, if requested.

As a small business, Atlantic does not have the capability of forward pricing its indirect rates, but uses the current rates bid to extend into the future (unless there are significant future business changes that we are aware of at the time of submittal). The indirect rates used are based on an evaluation of our current 9-month "actuals" calculation and then making several assumptions as to how the last 3 months of our Fiscal Year may alter the current actual rates.

There is no Government Furnished Property, Equipment or Data (GFP/GFE/GFD) proposed on this program.

Our cost proposal is valid for a period of 90 days. Since our Fiscal Year begins on 1 July, we reserve the right to update our indirect rates based on the new FY00 business plan and FY99's "actuals" since our fiscal year closes on 30 June.

If you have technical questions or comments, please feel free to call Dr. William McKinzie on (301) 982-5271. All questions of a contractual nature should be directed to me on (301) 982-5270. My fax number is (301) 982-5297. Or, you may e-mail me on: tmarangi@erols.com.

B. EXECUTIVE SUMMARY

A reconfigurable aperture ultimately allows for a reduction in the number and type of antennas on a platform that are required by it's electronic equipment. One trend toward simplification has been development of multi-function apertures, where federations of broadband elements are reconfigured via switchable beamformers and feeds. Atlantic Aerospace has demonstrated an efficient electrically small aperture at UHF [ref: B-1] that is reconfigurable over time-frequency. This antenna has been used aboard an F-15 for SATCOM, and is currently being enhanced for reconfigurability between SATCOM and line-of-sight communications. For the current antenna, the two SATCOM functions, receive and transmit, are sequenced in the time domain. Sequencing additional functions in the time domain using the same aperture has been studied during the development of some multi-function apertures for ESM, Data Link and CNI functions and determined to be feasible, given some changes to operational concepts.

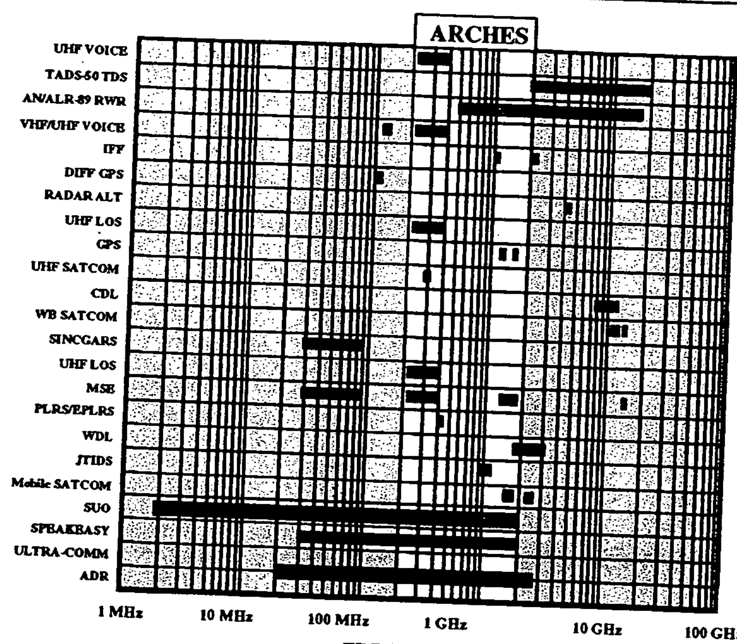


Figure B-1. Map of Military Function Versus Frequency

Figure B-1 provides a sampling of the large number of current military electronic functions, some or all of which are deployed on current military weapon systems. The SUO band is the largest, covering from 2 MHz to 2 GHz, and presents a significant challenge because, in this case the platform is a soldier. A reconfigurable aperture here may also be able to self-optimize link closure. DARPA's ULTRA-COMM program has demonstrated an advanced digital receiver capable of covering 20 MHz to 2800 MHz and will support the ARMY's Speakeasy and JTRS programs. Airborne low band ESM/SIGINT also presents a difficult antenna challenge because of the typically large aperture sizes. In fact, an ESM system would be ideal application for a reconfigurable array because of its robust beamwidth, bandwidth and polarization requirements. **Our proposed program addresses these significant military needs by developing and demonstrating a 200 MHz to 2 GHz reconfigurable antenna. The resulting technology will be scalable to higher frequencies, including C-Band through Ku-Band and above.**

This proposal presents a program for the development and integration of electronically controllable Antenna elements with an electrically thin, lightweight **RE**configurable High impedance Electromagnetic Surface (**ARCHES**). Such an integrated aperture structure

This proposed ARCHES effort contributes to each of the four areas of technical interest in BAA 99-19 as illustrated in Figure B-3. We feel that the greatest advance to the state of the art represented by this program is in the area of integrated groundplane technology (II). Additionally, the proposed broadband reconfigurable magnetic conductor is potentially applicable to core technology developments in element reconfiguration techniques. We have chosen a unique moderate bandwidth reconfigurable monopole element that does not require a balun when installed on this AMC. This element is considered core technology (I) because it also applies to any reconfigurable high impedance surface. Other radiating elements, such as broadband bowties or spirals, could also be considered. Another critical component of this effort is the development of models (III) that allow simulations of array performance with all interactions between array elements and the AMC structure rigorously included. This will result in a computer tool that will be able to predict performance of ARCHES arrays. Laboratory demonstrations (IV) of a hardware implementation of Figure B-2 will be carried out to verify electrical performance. A more detailed description of the relationship between the ARCHES proposal and the BAA areas of interest follows.

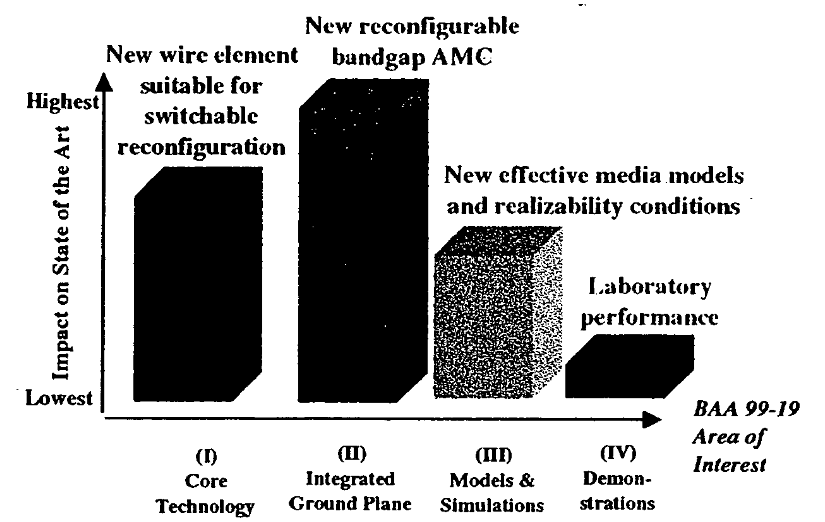


Figure B-3. Qualitative ARCHES Technology Assessment

(I) Core Technology – The ARCHES effort makes use of existing core technology as well as contributes to it with a new balun-less reconfigurable antenna element. We will use mature low risk components for switches to reconfigure the radiating elements and the AMC. At present, p-i-n diodes are the best choice to reconfigure the monopole radiating elements. An example using these switches is given in Figure B-4 for a reconfigurable SATCOM aperture developed by Atlantic Aerospace for conformal installation on tactical fighter aircraft. Here, p-i-n diode switches connect metallic bars to a microstrip patch and are either open or closed to provide a large number of discrete states of efficient aperture operation within the SATCOM band. Like the bent wire monopole element, this antenna utilizes a fixed feed (no traditional matching network) and bias voltages are used to control the diode switches. Varactor diodes are an alternate choice for reconfiguring the AMC and both of these could be replaced by MEMs switches in the future.

(II) Integrated Groundplane Technologies – The reconfigurable bandgap AMC is at the heart of our approach and is the key technical innovation of the ARCHES program. The basic 2-layer reactive AMC design can be modeled as a length of transmission line terminated by a short circuit as illustrated in Figure B-5(a). A narrow band AMC demonstrator is shown in

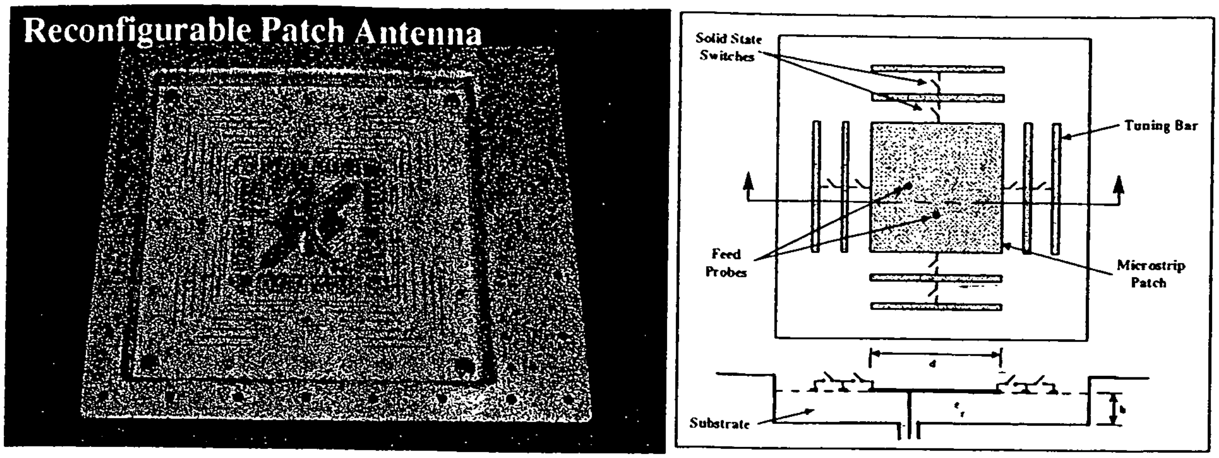


Figure B-4. Example of a frequency-reconfigurable patch antenna covering the SATCOM band 240 - 320 MHz.

Figure B-5(b). Measured gain of the demonstrator is provided in Figure B-5(c). The data show high antenna gain over a 10% bandwidth (half power), which corresponds to the ±90° reflection phase bandwidth plotted in Figure B-5(d). Under this proposal, instantaneous bandwidth will be increased by increasing the inductance of the transmission line section by using either lumped

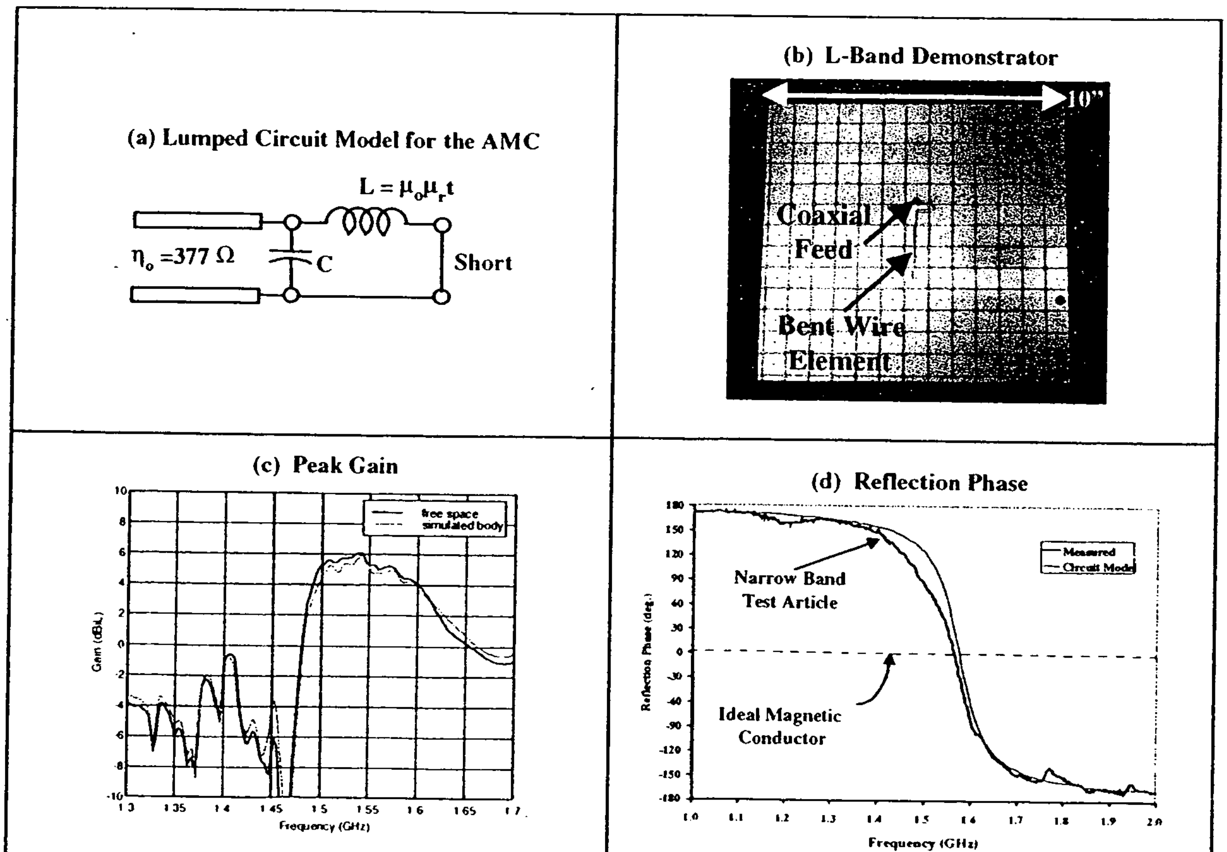


Figure B-5. Summary of a bent-wire monopole radiating on a narrow band AMC, or high impedance surface

components or low loss magnetic materials in the AMC construction. AMC bandwidth is expected to increase to 2:1 using this approach. To realize a reconfigurable AMC, the resonant frequency of the AMC will be varied by adjusting the value of the circuit capacitance or inductance. One proposed method for achieving this variability involves electrically connecting and disconnecting conducting plates of differing sizes within the AMC. The bandgap can then be tuned in frequency over a bandwidth approaching 10:1.

(III) Design, Modeling & Simulation – Successful exploitation of the ARCHES concept will depend on the development of accurate and efficient models that capture the physics of the AMC. Most of the developments with narrow band high impedance band gap structures have been empirically derived. The ability to predict TE and TM surface wave modes in the structure is critical because these modes must be suppressed. Effective media models will be developed and used to derive realizability conditions relating achievable bandwidths to AMC design parameters. These models will also be used to quantify bulk constitutive parameters that will be used in more rigorous techniques, such as spectral domain method of moments, for computing element-to-element interactions.

(IV) Demonstrations – Several laboratory measurements will be made to quantify the performance of breadboard hardware. Element and array patterns will be made at various frequencies in an anechoic chamber. Element input impedance and mutual coupling measurements will be made for various reconfiguration states.

Schedule & Cost - The proposed period of performance for the ARCHES program is 24 months, followed by a 2-month reporting period. A high level program schedule is provided in Figure B-6. The schedule lists tasks, identifies task durations, and lists costs by task and by year for all of the technical tasks. The total program price is $2,539,499. The funding profile assumes an FY00 start, but an earlier start can be easily supported if FY99 funds are available.

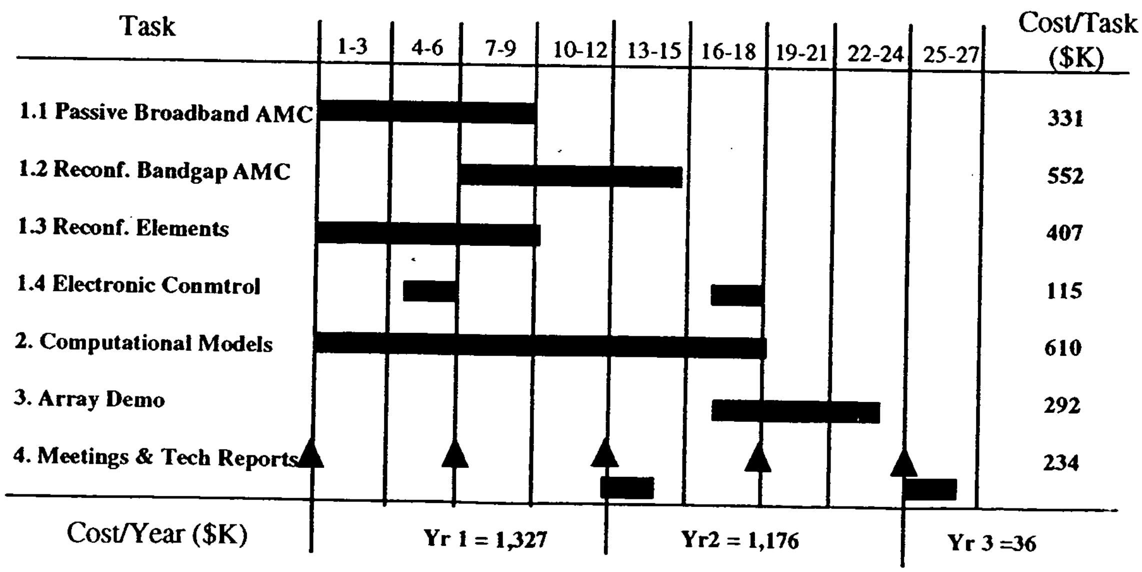


Figure B-6. Major task schedule & Cost Summary

C. INNOVATIVE CLAIMS

Table C-1 summarizes the innovative claims for each area of interest in the RECAP BAA. The reconfigurable radiating element used in ARCHES is considered to be core technology because it can also be used with other reconfigurable high impedance surfaces. The reconfigurable radiating element utilizes existing reconfigurable switch technology, but could use future switch components, from other core technology efforts, as they mature and become available. The reconfigurable bandgap AMC is considered to be the forefront in integrated groundplane technology. It is the primary innovation of this effort and is expected to find application in other reconfigurable aperture systems. The computer modeling tools will be unique in their ability to characterize anisotropic band gap structures by bulk permitivity and permeability tensors. Since we are still dealing with passive structures, realizability conditions are important and will be derived for the basic two-layer structure. The final computer code will utilize these models and be able to accurately predict ARCHES array performance. The demonstration of an efficient reconfigurable array that is electrically thin ($< \lambda_{max}/10$), lightweight (< 2 lb/ft^2) and covers a decade of bandwidth has never been done before. All of these results can be scaled up in frequency. As discussed in Section-F, the large number of potential DoD applications for ARCHES technology will warrant fabrication of an array for demonstrating a specific military function in year-3 of the program.

BAA Area	Innovative Claim
I. Core Technology Development	A new radiating element that lies close to a high impedance surface, requires no balun, and can be reconfigured for different frequency bands by simple SPST switches.
II. Integrated Groundplane Technology	1) A new broadband bandgap artificial magnetic conductor which creates a high impedance surface with zero phase shift suitable for supporting a wide variety of reconfigurable array elements. 2) Techniques for electronically reconfiguring the AMC bandgap center frequency using a) adjustable sheet capacitance in the FSS layer using PIN or varactor diode control, and b) adjustable effective permeability of the AMC spacer layer using reconfigurable artificial magnetic molecules.
III. Design, Modeling & Simulation	1) New effective media models and derived conditions of realizability for artificial magnetic media. 2) A computer code that will predict reconfigurable array performance
IV. Demonstrations	Computer-controlled reconfigurable array covering a decade bandwidth

Figure C-1. ARCHES Technical Innovation

D. PROPOSED STATEMENT OF WORK

D.1 Program Goals

This research program will develop an integrated groundplane comprised of electrically-thin periodic structures with surface wave bandgap properties, reconfigurable radiating elements, and techniques for integration of the two to produce a reconfigurable antenna system. Specific technical objectives are as follows.

a) Develop a passive AMC with an operation bandwidth of 2:1
b) Develop a reconfigurable AMC with an operational bandwidth of 10:1
c) Develop reconfigurable radiating elements to radiate efficiently when mounted on, or integrated within, the AMC structure
d) Develop, validate, and use a computational tool for efficient analysis of the reconfigurable radiators when integrated into an AMC

See Section H herein for a detailed discussion of the technical approach and supporting technical rationale for achieving these objectives.

D.2 Program Task Descriptions

This section presents a concise description of the technical effort performed in each task of the proposed program. These tasks are mapped directly into the program schedule presented in Section G, and the Work Breakdown Structure of the cost proposal (see separate cost volume). Atlantic Aerospace is hereinafter referred to as AAEC, and Arizona State University is referred to as ASU.

Task 1.0 Integrated Ground Plane (IGP) Technology Development. The purpose of this task is to conduct fundamental research and technology development needed to realize broadband and/or reconfigurable AMCs and embedded reconfigurable radiating elements. This is the primary technical task of the program.

Task 1.1 Passive Broadband AMC Development. AAEC shall investigate, design, model, fabricate, and test a number of concepts for increasing instantaneous bandwidth of high impedance surfaces. These surfaces shall consist of multi-layer printed circuit boards, properly designed for AMC behavior, and augmented with bandwidth enhancing components or treatments. Approaches that shall be considered include integral printed inductors, SMT chip inductors, low loss magnetic beads, and thin internal magnetic layers. Candidate approaches shall be first evaluated using full wave computer simulations using TLM (Micro-Stripes) and/or FEM (HFSS) codes. Test articles of most promising designs shall be fabricated. Free space S11 measurements shall be conducted to confirm AMC operational frequency and reflection phase bandwidth. This task shall produce AMC designs and hardware demonstrators with 2:1 operational bandwidth within the 0.2 to 2.0 GHz band.

Task 1.2 Reconfigurable Bandgap AMC Development. Using the 2:1 bandwidth AMC from Task 1.1 as a starting point, this task shall pursue development of technologies for reconfiguring the AMC – that is, realizing a frequency tunable high impedance surface. Preliminary concepts include reconfiguring the effective capacitance of the AMC printed layers using PIN diodes,

varactor diodes or other switch mechanisms, reconfiguring the effective media permeability of appropriate AMC layers using arrays of circuit-loaded artificial magnetic molecules, or through the use of DC biased magnetic materials. As in Task 1.1, candidate approaches shall be evaluated using computer simulations, test articles of most promising designs shall be fabricated, and verification tests shall be conducted. The electronic controller developed in Task 1.4.1 shall be used to reconfigure the test articles. This task shall produce reconfigurable AMC designs and hardware demonstrators with 2:1 instantaneous bandwidth and 10:1 operational bandwidth within the 0.2 to 2.0 GHz band.

Task 1.3 Reconfigurable Radiating Element Development. AAEC shall develop reconfigurable antenna elements for use with the AMCs developed in Tasks 1.1 and 1.2. Preliminary concepts include bent wire monopoles, embedded loops, and other wire structures, slot elements in the RF back-plane, and slotline excitation of gaps in the upper layer of a high impedance surface. These elements will incorporate electronic switches for element reconfiguration. Baseline switches will be PIN diodes, however, MEMS RF switches will also be considered. Candidate approaches shall be evaluated using computer simulations, test articles of most promising designs shall be fabricated, and verification tests shall be conducted, including impedance match, bandwidth, radiation pattern, polarization, and gain. This task shall produce reconfigurable antenna designs and array element demonstrators with 10:1 operational bandwidth within the 0.2 to 2.0 GHz band.

Task 1.4 Electronic Controller Development. AAEC shall develop software and digital hardware to control an array of reconfigurable radiating elements and a reconfigurable AMC. The controller shall consist of a COTS personal computer, custom software, and a custom digital assembly that will provide analog control signals for antenna and AMC switches. This task shall produce control electronics needed for the antenna demonstrations in Task 3.

Task 2.0 Computational Tool Development. The purpose of this task is to develop electromagnetic modeling, simulation, and design tools. Necessary advances provided by these tools include the capability to rapidly model candidate designs (design tool vs. analysis tool), and rigorous analysis of integral AMC and radiating elements. The bulk of this task shall be performed by a select team of ASU researchers.

Task 2.1 Identification of Desired Equivalent Media Properties. ASU shall determine the fundamental waveguiding properties of a layered anisotropic medium which presents a high surface impedance with maximum frequency bandwidth, corresponding to a region in the ω–β diagram that cuts off all or most surface waves. This task shall produce the required permeability and permittivity tensor properties that result in maximum AMC performance (i.e., bandwidth).

Task 2.2 Fast Solver Development. ASU shall develop fast solver algorithms to analyze AMC structures. Candidate approaches include specialization of a Laplace equation solver and/or a Diffusion equation solver to obtain efficient quasi-static analysis of the arbitrary material structures in a periodic unit cell, and modification of a time domain PDE Maxwell equation solver with Heaviside limits. This task shall produce codes that rapidly predict AMC performance, which otherwise require many hours to analyze using full-wave Maxwell solvers.

H. TECHNICAL APPROACH

The overall technical goals of this program are: 1) To demonstrate an electrically-thin, frequency reconfigurable, antenna array operational over a 10:1 bandwidth (0.2 to 2 GHz) with a relatively constant directivity, no grating lobes, a fixed main beam, and linear polarization, and 2) To develop and validate an integrated ground plane computational tool for efficient analysis of radiators in complex periodic structures (i.e. AMCs).

H.1 Array Technology

Fundamental to our approach is the concept of an artificial magnetic-conductor (AMC). One example is the high impedance surface reported by Sievenpiper and Yablonovitch [H1]. It's basic physical features are as shown in Figure H-1.

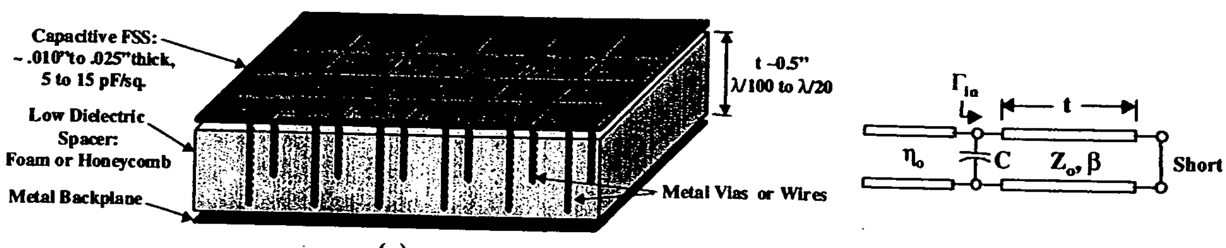


Figure H-1. (a) An example of a UHF (350 MHz) artificial magnetic conductor (AMC), (b) Equivalent circuit model for an AMC with normally incident plane waves.

To achieve the array goals, we will develop high-impedance surfaces as follows:

1) Create AMC's with increased bandwidth for the surface wave bandgap. The goal is a 2:1 bandwidth using passive techniques for λ/50 thick structures (see Fig. H-2(b)).
2) Create AMCs whose bandgap center frequency is reconfigurable over a 5:1 ratio under electronic control (see Fig. H-2(c)).
3) Create electronically reconfigurable or switched elements, embedded on or in AMCs.

Both a broader bandwidth AMC and a reconfigurable AMC are needed to achieve a decade of operational bandwidth.

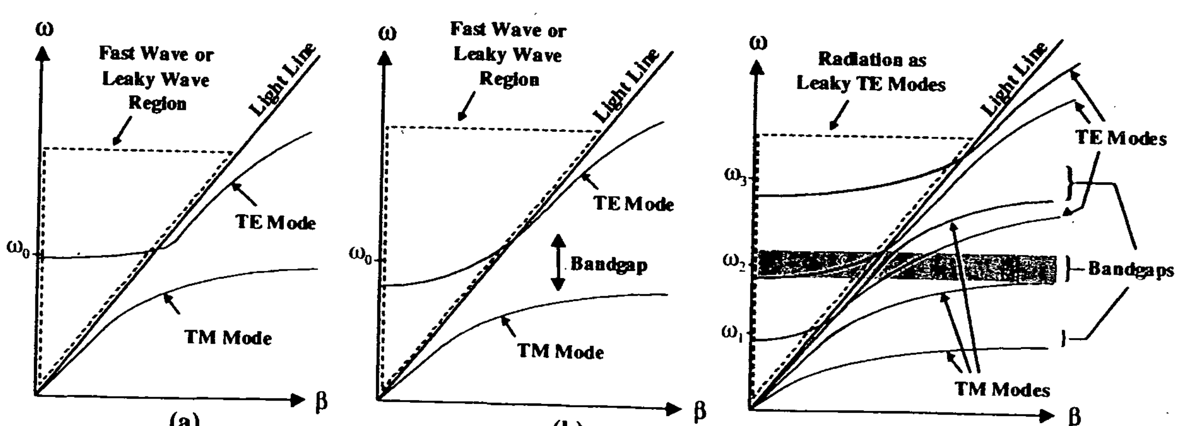
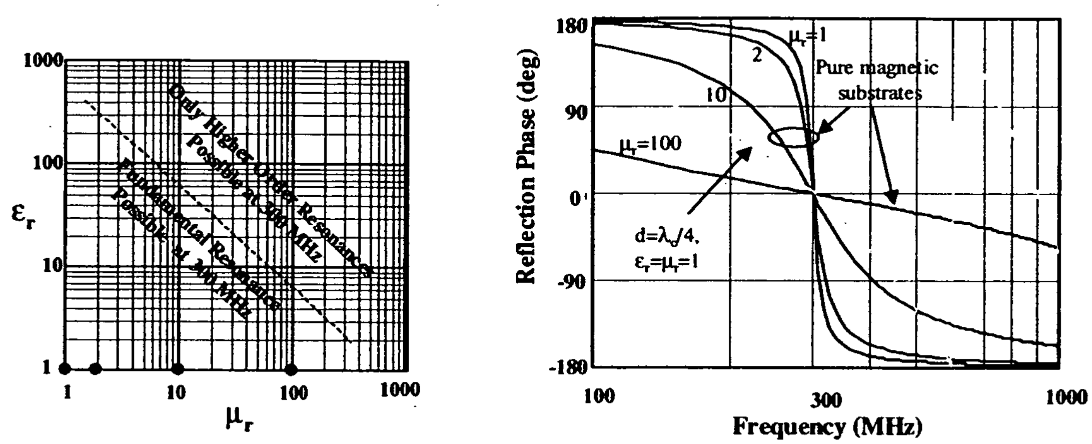


Figure H-2. (a) Conventional AMC, (b) broadband AMC, (c) reconfigurable bandgap AMC

H.1.1 Broadband AMC Concepts

Pure magnetic materials in the spacer layer of an AMC (between the RF backplane and FSS) will not only lower the resonant frequency, but will also broaden the reflection phase bandwidth. To understand this phenomena more clearly, consider the transmission line circuit model of Figure H-1(b). Thickness t is fixed at 1 cm, and the effective FSS sheet capacitance, C, is adjusted for resonance at 300 MHz for a number of cases presented below ($t = \lambda_o/100$, λ_o=1m).

Figure H-3(a) illustrates the ε_r-μ_r space theoretically available for the spacer layer. The characteristic impedance, Z_o, is defined as $\eta_o(\mu_r/\varepsilon_r)^{1/2}$ where $\eta_o=377\Omega$. Four points are highlighted on the μ_r axis, which corresponds to pure magnetic materials, and the reflection phase for each case is plotted in Figure H-3(b). Now **the +/-90° phase bandwidth corresponds to the range of frequencies over which high surface impedances are demonstrated, as well as the surface wave bandgap.** This statement has been asserted by Sievenpiper, supported by his surface wave measurements, and supported by AAEC's swept gain measurements on bent wire monopoles, where high element gain and good VSWR is obtained only in the bandgap.



(a) (b)

Figure H-3. Magnetic materials will dramatically increase AMC bandwidth: (a) ε_r-μ_r space with four pure magnetic material values chosen, (b) predicted reflection phase using the circuit model.

The AMC bandwidth for these cases is summarized in Table H-1. **More than a decade of bandwidth (actually 30:1) can be achieved if an effective μ_r of 100 can be realized.** As a reference case, a $\lambda_o/4$ air spacing (yellow curve) yields a 3:1 phase bandwidth.

Table H-1. Reflection phase bandwidth for Figure H-2(b).

μ_r	+/- 90° Phase Bandwidth
1	6.26%
2	12.5%
10	59.5% (1.85:1)
100	30:1

Magnetic thin films may be considered attractive for extending the phase bandwidth. However, conventional low loss films are magnetodielectric with $\varepsilon_r \sim \mu_r$, as opposed to pure magnetic. Figure H-4 maps magnetodielectric space into reflection phase for the same thickness AMC as used in Figure H-3. The +/-90° phase bandwidths are summarized in Table H-2. We conclude that a 3:1 phase bandwidth is a fundamental limit for magnetodielectric materials where $\varepsilon_r=\mu_r$. So the use of magnetodielectric films alone will not achieve our 10:1 bandwidth goal for the proposed array.

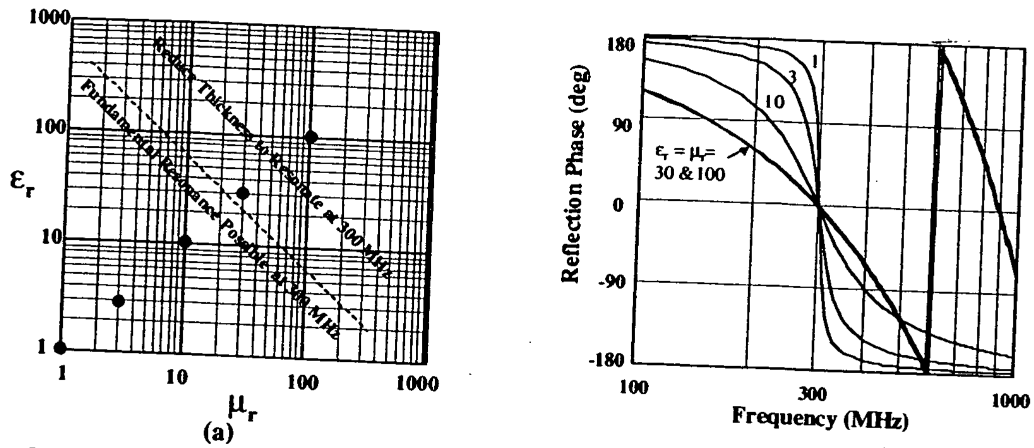


Figure H-4. Magnetodielectric materials will increase AMC bandwidth up to a 3:1 limit: (a) ε_r-μ_r space with five values chosen, (b) predicted reflection phase using the circuit model.

Table H-2. Reflection phase bandwidth for Figure H-3(b).

$\varepsilon_r=\mu_r$	+/- 90° Phase Bandwidth
1	6.3%
3	18.6%
10	59% (1.83:1)
30	100% (3:1)
100	100% (3:1)

Instead of magnetodielectric films, we propose to evaluate four alternate techniques, using lower cost materials, to increase AMC bandwidth. They are 1) inductors embedded in the FSS layer, 2) inductors embedded inside of the AMC spacer layer, 3) embedded magnetic beads, and 4) embedded magnetic tiles.

The objective of the first method is to create a frequency-dependent capacitive FSS so that the effective C is lowered at higher frequencies. Schematically, this is illustrated in Figure H-5(a), and two possible implementations are shown in Figures H-5(b) & (c) where top views of an FSS layer are shown. In Figure H-5(b), chip inductors could be inserted into the narrow lines between the center via and the capacitive pads to tailor the frequency behavior. The mesh-patch array shown in Figure H-5(c) can also be augmented with series chip inductors integrated into the mesh. Design formulas for the simple mesh-patch array are given by Te-Kao Wu [H2].

The objective of the second method using embedded inductors is to increase the series inductance as illustrated in Figure H-6(a). The printed spiral of Figure H-6(b) could also be

fabricated interior to the spacer layer using a multilayer PC board fabrication. Larger value inductances, and potentially switched inductances, could be introduced using the method shown in Figure H-6(c). Here, discrete chip or air core inductors are surface mounted to PC boards whose width defines the thickness t of the spacer layer.

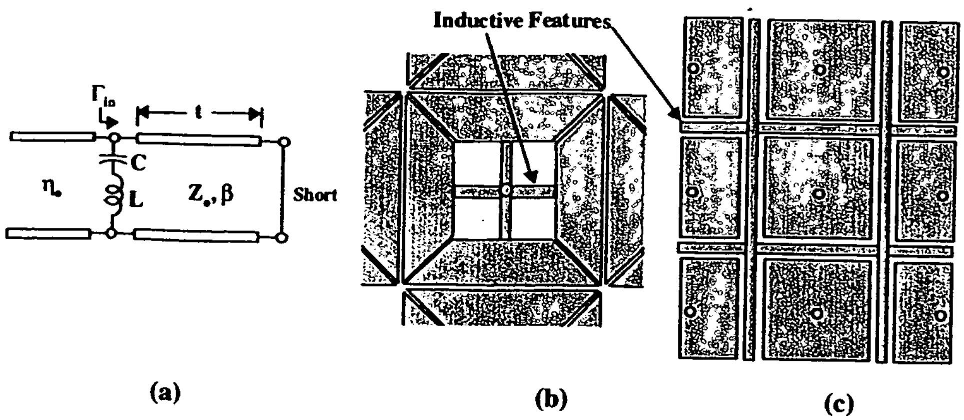


Figure H-5. Concepts for introducing inductors into the FSS layer of an AMC structure.

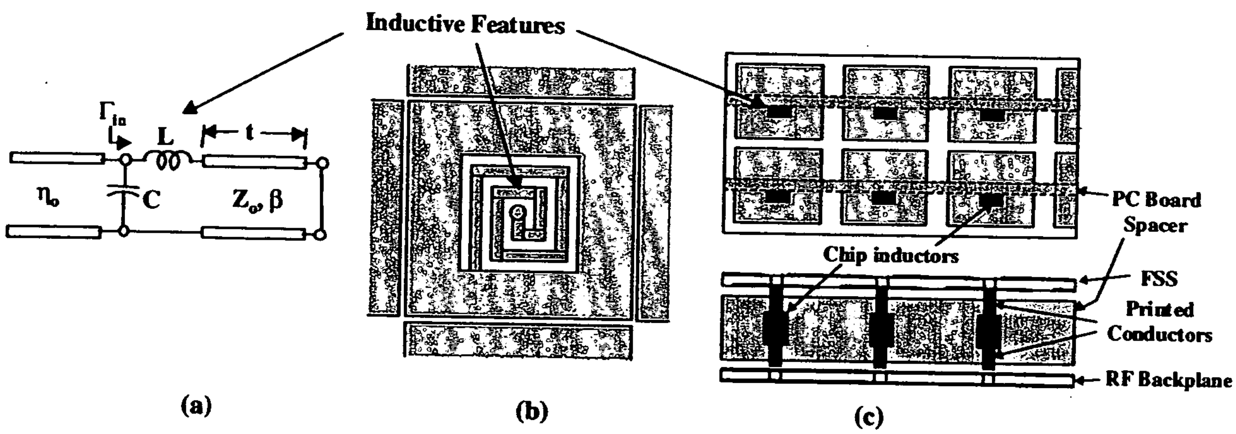


Figure H-6. Concepts for embedding inductors inside an AMC structure.

The introduction of magnetic materials to load the AMC may be realized by at least two techniques as shown in Figure H-7(a) & (b). The first method involves placing a magnetic bead around each via wire between the FSS and the RF backplane. This will dramatically increase the via inductance. The second technique is to replace the low dielectric constant spacer layer with flat magnetic tiles, drilled to accept the via wires. Initial surveys have identified a NiZn alloy (material 4E1 from Philips) as a low loss magnetic material whose μ_r~15. This is the value of permeability required to achieve a passive AMC with a 2:1 bandgap bandwidth. The dominant risk is the availability of materials with low loss magnetic properties at L-band frequencies.

We propose to evaluate, computationally and experimentally, all four of these basic approaches for improving the AMC bandwidth (increasing the bandgap). They will be modeled using full-wave time-domain TLM and frequency-domain FEM analysis tools (KCC Micro_stripes and Ansoft HFSS, respectively), each of which is capable of modeling the plane

wave reflection coefficient given details of the unit cell geometry. L-band and UHF phase measurements will confirm performance.

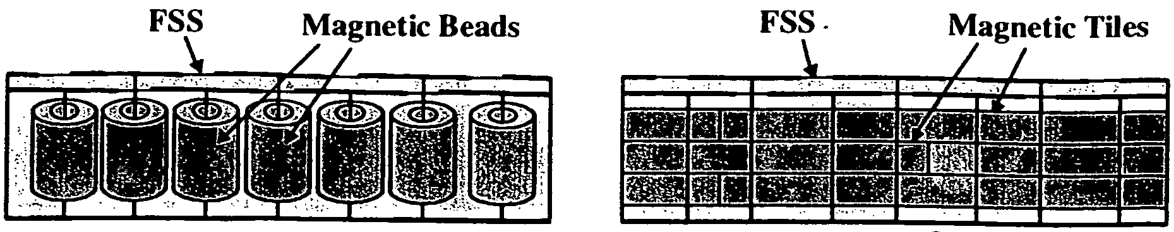


Figure H-7. Concepts for embedding conventional magnetic materials into an AMC structure for improved bandwidth.

H.1.2 Reconfigurable AMC Concepts

We define a reconfigurable AMC to be a high impedance surface whose bandgap center frequency can be electronically adjusted to cover an operational bandwidth much wider than the bandgap. This is illustrated in Figure H-2(c). The goal of this research is to cover a decade of operational bandwidth.

Two basic approaches are identified for AMC reconfigurability: 1) Modify the FSS effective sheet capacitance, which can be done discretely with PIN diode switches or continuously with varactor diodes and 2) Modify the effective permeability of the spacer layer, which can be realized using electronically-loaded artificial magnetic molecules.

Consider the first method. Since Atlantic Aerospace has extensive experience in using PIN diode switches for reconfigurable patch antennas (see Sections I and K), we can build on our current success to incorporate such switches into an integrated ground plane. An example is shown in Figure H-7 in which the FSS is discretely reconfigured through 16 unique switch states using four PIN diodes per unit cell.

The basic concept in Figure H-8 is to reconfigure the effective sheet capacitance of an FSS by using PIN diode switches. Surface mounted diodes are used to change the size of overlapping printed patches. The OFF state capacitance of the diodes is lumped with or absorbed into the parasitic capacitance between FSS patches. So no resonating inductors are required to maintain a high open circuit impedance. The vias, indigenous to the high-impedance surface, are used to route bias currents and voltages from stripline control lines buried inside the RF backplane. Current limiting resistors and RF decoupling caps may be surface mounted on the underside of the RF backplane as shown in Section AA of Figure H-8. However, the decoupling capacitors may not even be needed if sufficient capacitance to ground is designed into the bias control striplines. Four diodes per unit cell each switch a non-uniformly sized capacitive patch to yield 16 unique tuning states for a wide range of effective capacitance, as seen by y-polarized E fields. We predict the range of effective capacitance to be about 25:1, which would yield a 5:1 ratio of reconfigurable AMC center frequency.

We propose to control the hundreds of PIN diodes by driving large sections of the AMC surface (100 unit cells at a time) in parallel using medium current (.3 to 1.0 Amp) programmable PIN diode driver circuits, which are essentially programmable voltage sources. This concept is shown in Figure H-9. Since four diodes will share the same current limiting resistor, the forward bias voltages are programmable in discrete values. This will help to maintain a constant diode current for all switching states.

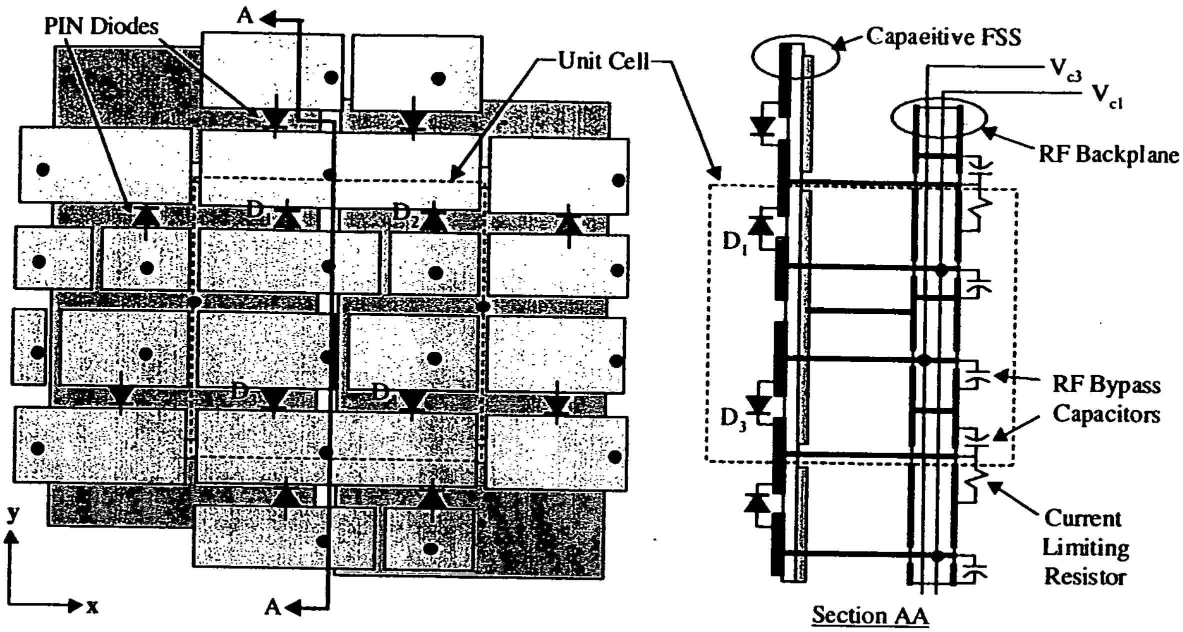


Figure H-8. PIN diode switches embedded in the FSS layer yields a discretely reconfigurable AMC.

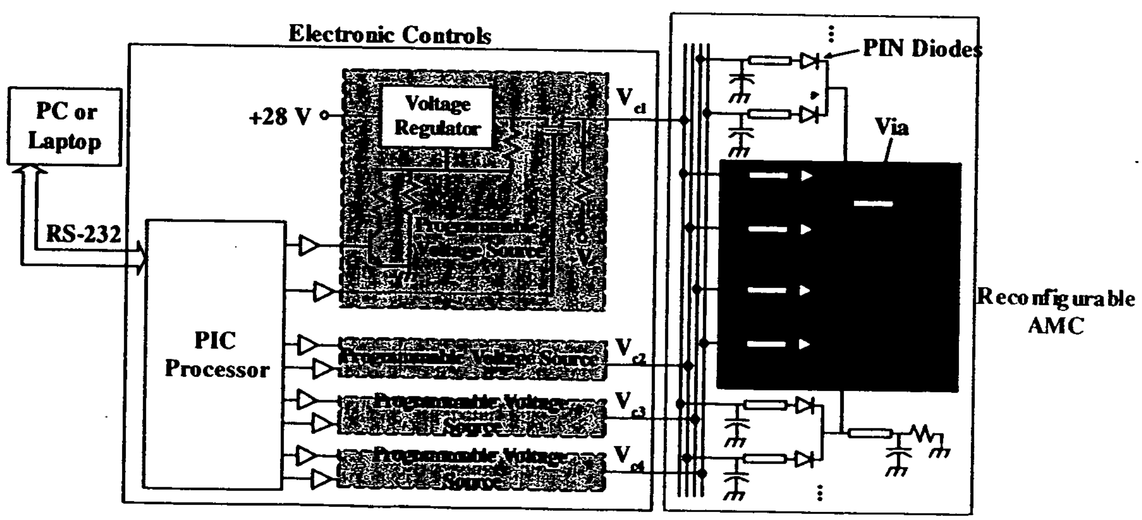


Figure H-9. A microcontroller-based PIN diode control circuit will discretely adjust the FSS effective capacitance in a reconfigurable AMC.

Another means of electronically reconfiguring the effective capacitance of the FSS layer is to connect varactor diodes between capacitive patches as illustrated in Figure H-10. A continuously reconfigurable capacitance is offered to y-polarized E fields. This technique uses fewer diodes than the switchable approach (PIN diodes), and only one control voltage is needed for the entire AMC structure. Therefore, the electronic controls become simpler than Figure H-9, requiring only a microcontroller and a buffered A/D converter. Another merit is that the varactor approach is a very low power technique for AMC reconfigurability. However, one of the risks is that all varactors must be as well-matched as possible with respect to the C-V curve for uniform performance of the surface.

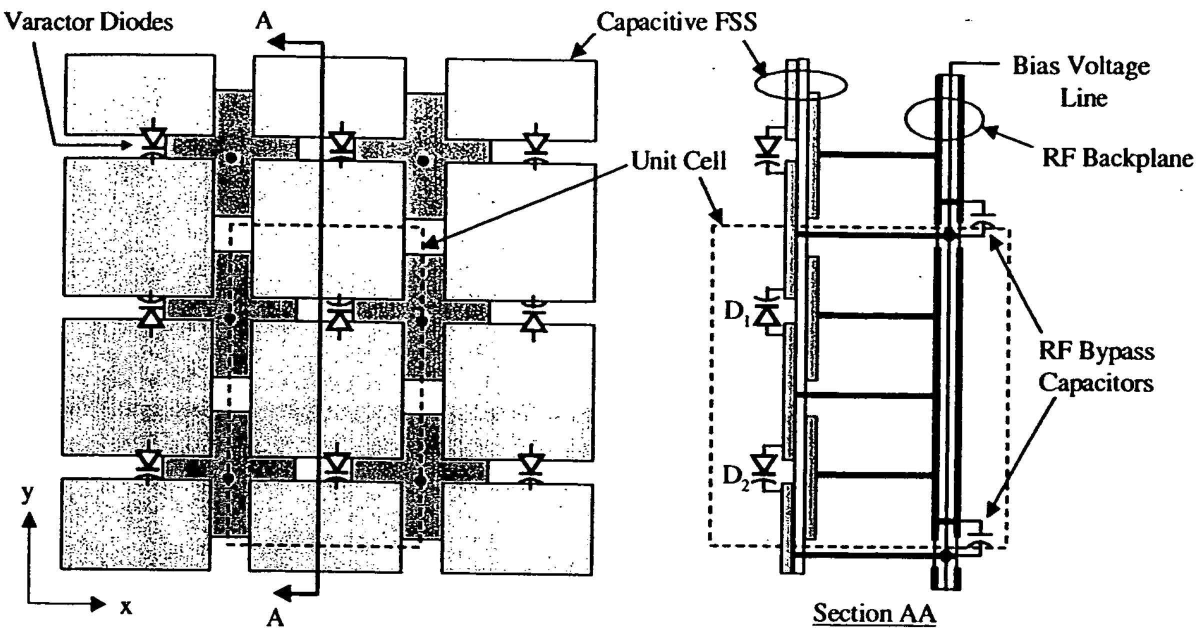


Figure H-10. Varactor diodes, surface mounted on the FSS layer, yield a continuously reconfigurable AMC.

The anticipated tuning range for effective FSS capacitance using varactor diodes is about 4:1 at best, given the inherent limitations of about a 10:1 ratio for varactor capacitance and the parasitic capacitances inherent in the FSS structure. The varactor approach may be combined with the PIN switches to achieve fine tuning if the available switch states using PIN diodes alone are insufficient to cover contiguously the 10:1 operational bandwidth. Research on passive broadband AMC's (Task 1.1) will help to define these bandwidth issues.

Now consider the second basic approach to reconfiguring the AMC bandgap, where we propose to modify the effective permeability of the spacer layer, while maintaining a constant low value for the effective permittivity. To do this we propose an array of tunable or switched-frequency artificial magnetic molecules. An artificial magnetic molecule is an electrically-small conductive loop (magnetic dipole) whose dipole moment may be electronically reconfigured by changing a series load impedance [H3]. In 1998, Atlantic Aerospace funded an internal IR&D program which showed that arrays of capacitively-loaded artificial magnetic molecules can yield an anisotropic effective media characterized by a medium permeability (μ_r = 5 to 15) and a low

permittivity (ε_r~2.5). However, this desirable magnetic property is very frequency dependent, and hence must be tuned or reconfigured to be useful.

One geometry for an infinite 3-D array of artificial magnetic molecules is shown in Figure H-11. This is a body-centered hexahedron lattice with loops lying in the y-z plane, and plane wave propagation in the z direction. Full-wave, time-domain, TLM calculations were performed using Micro_stripes to model this structure. The results are shown in Figure H-12.

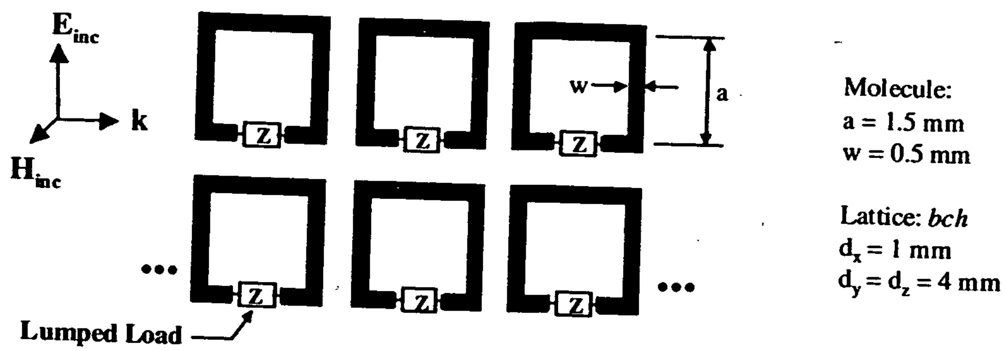


Figure H-11. An array of capacitively-loaded, electrically-small loops (artificial magnetic molecules) will collectively resonate to create an equivalent anisotropic magnetic media with a significant magnetic moment perpendicular to the loops.

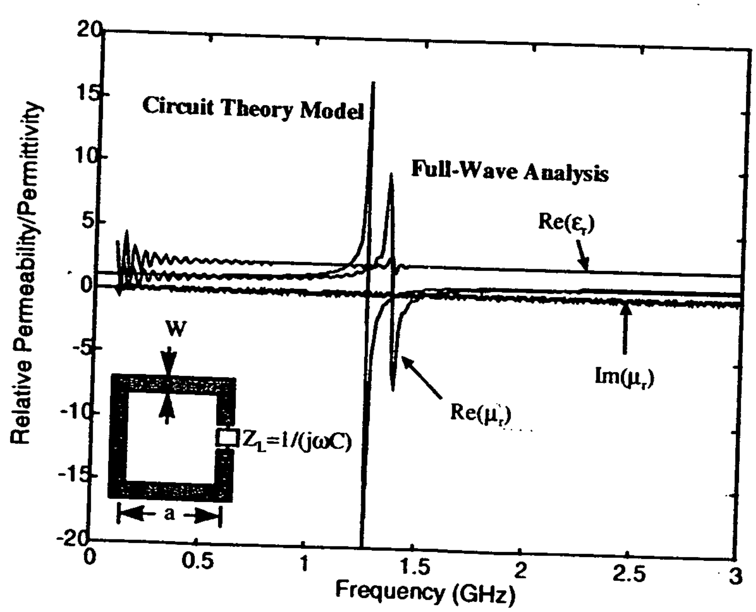


Figure H-12. Calculated effective media properties for the array of artificial magnetic molecules shown in Figure H-10.

The two significant features of Figure H-12 are 1) a constant, low value of permittivity (ε_r~2.5), and 2) a higher value of permeability (μ_r~10) which peaks over a narrow bandwidth.

The frequency at which the real part of μ_r transitions from positive (paramagnetic) to negative (diamagnetic) is the molecular resonance frequency, and at this frequency the loop currents become very large for lossless molecules (loops and loads).

The effective permeability may be defined as $\mu_r = 1 + N\alpha$ where N is the number of molecules per unit volume and α is the magnetic susceptibility of an individual molecule. A simple circuit model for susceptability has been shown to be accurate to within about 10% for predicting molecular resonance, as well as providing physical insight. Using Faraday's Law, and treating the loop as electrically small, α can be derived as $\alpha = \frac{m}{H} = \frac{-j\omega\mu_0 a^4}{R_{rad} + j\omega L_{loop} + Z_L}$ where a^2 is the loop area, R_{rad}~0 is the loop radiation resistance, and L_{Loop} is the loop inductance. If loaded by a capacitance C, the resonant frequency of the artificial molecule is simply $\omega_0 = \frac{1}{\sqrt{L_{loop}C}}$.

Adjustment of the AMC spacer layer permeability can be achieved from either of two mechanisms: 1) the variations in molecular resonance ω_o, or 2) variations in the molecular density N. Circuit implementations for each mechanism are described below.

To realize a reconfigurable molecular resonance, consider the AMC cross sectional view shown in Figure H-13. The circuit loads for each loop, namely varactor diodes and their RF decoupling networks, can be hidden behind the RF backplane, or located very close to the backplane where tangential electric fields are near zero and RF coupling into DC bias lines would be minimal. A candidate circuit for the tuning network of a given row is shown in Figure H-14. Ballast resistors R_n ensure an equal bias voltage is dropped across each diode. Assuming the AMC contains multiple rows of loops with equal numbers of molecules, then the electronic controls are relatively simple, as a single bias voltage can reconfigure the entire AMC.

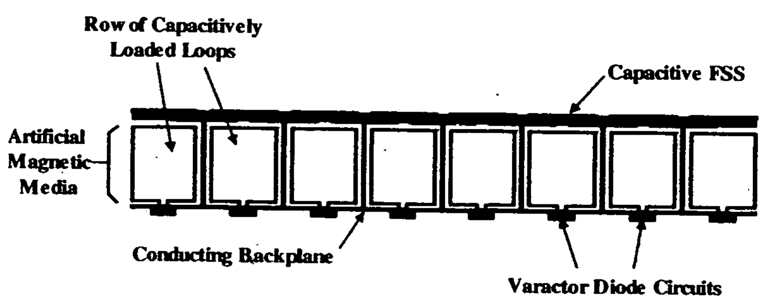


Figure H-13. A reconfigurable AMC can be realized with a tunable artificial magnetic media and tuned with varactor diodes.

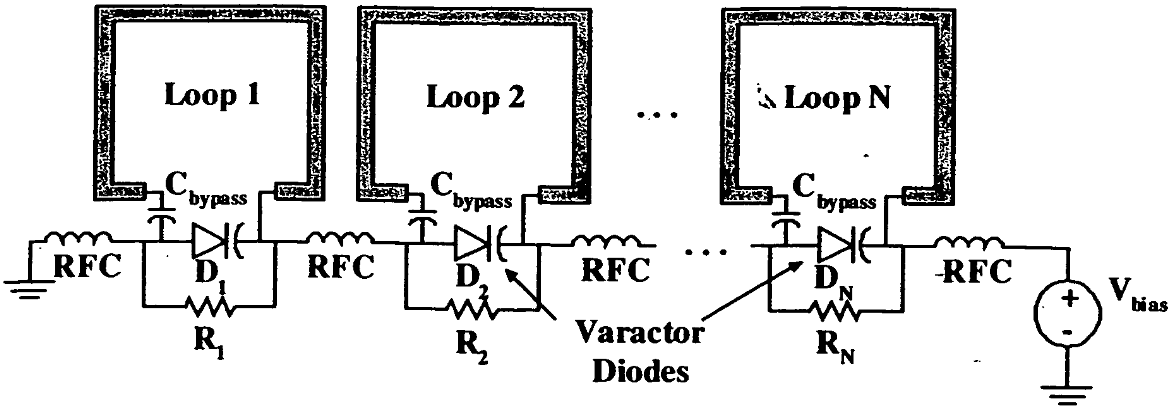


Figure H-14. A possible circuit realization for varying the artificial molecule resonance.

Preliminary circuit calculations show that an 8:1 ratio change in capacitive load (typical for a varactor) will yield a 2.82:1 change in molecular resonance, which in turn, can also yield a 2.82:1 ratio change in bandgap center frequency **without a capacitive FSS layer!** (C=0 in the circuit model of Figure H-1(b)) This is illustrated in Figure H-15 where molecular resonances of 250, 300, 500, and 707 MHz are defined. (L_{loop}=30 nH, a=5 mm, N=2, d_x=d_y=d_z=1.2a). The reflection phase for a 0.4" thick AMC is plotted in Figure H-15(b), and the center frequencies are highlighted with matching color dots. Reflection phase bandwidths are predicted to be very narrow, but this is based on simple circuit models for μ_r where no radiation losses from loops are included. Full-wave modeling should predict broader bandwidths.

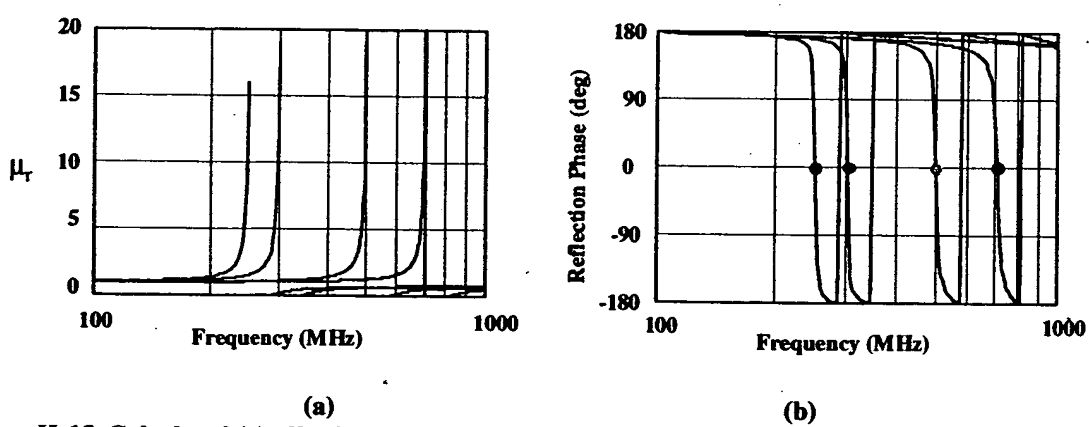


Figure H-15. Calculated (a) effective permeability and (b) reflection phase for a reconfigurable AMC using variable resonance artificial magnetic molecules.

The second mechanism for reconfiguring the effective permeability of an artificial magnetic media, comprising the AMC spacer layer, is to electronically vary *N*, the volume density of molecules. Let the varactor diodes of Figure H-14 be replaced with a series fixed capacitor and a SPST switch, where all of the switches in a given row are either open or closed simultaneously. Figure H-16 illustrates a possible circuit implementation of this idea. If some of the rows in a reconfigurable AMC have open switches, then these loops will not support dipole moments (no loop currents) and *N* will decrease. When a higher percentage of rows have closed

switches, their loops contribute in-band dipole moments, and N is increased. Since $\mu_r = 1 + N\alpha$, it follows that effective permeability, and hence bandgap center frequency, is varied.

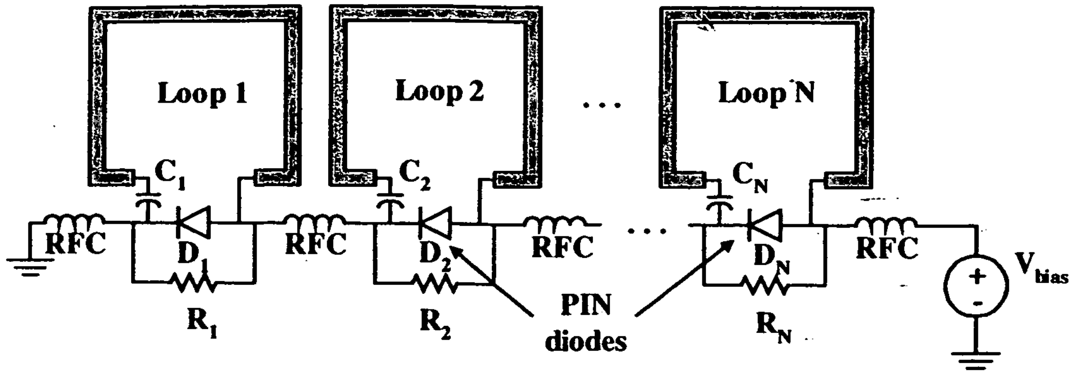


Figure H-16. A possible circuit realization for switching the density of artificial magnetic molecules.

It is conceivable to mix rows of switched and tunable artificial molecules to improve operational bandwidth. Each mechanism for reconfigurability will be evaluated rigorously using full-wave analysis tools and laboratory experiments.

H.1.3 Reconfigurable Element Concepts

Candidate antenna elements which are capable of being structurally integrated into an AMC will be evaluated computationally and experimentally. A subset of these element types is expected to be most compatible with the integration of RF switch technology, both existing and projected. The best candidates will be fabricated as reconfigurable elements, and tested for antenna performance as a function of switch configuration: input impedance bandwidth, mutual coupling, gain, beamwidth, etc.

The ability of a radiating element to couple into the dominant TE surface wave mode of an AMC is very important because TE modes are leaky only in the AMC bandgap. It is expected that candidate elements whose equivalent electric currents have a significant reaction with TE mode electric fields, or whose equivalent magnetic surface currents have a significant reaction with TE mode magnetic fields, will be efficient radiators. Candidate radiators may be considered modal transformers between the coaxial transmission line mode feeding an element, and surface wave modes. Figure H-17 below shows four promising element types, **non of which require the added complexity of baluns!**

Atlantic Aerospace has evaluated bent wire monopoles at L-band and UHF frequencies. Hardware prototypes are shown in Figures B-5 and H-18. Measurements have confirmed that only in the AMC bandgap can high gain (+4 to +6 dBil) and a good VSWR match be obtained. Typical 2:1 VSWR bandwidths are 5% to 10% for AMCs of thickness $\lambda/100$ to $\lambda/50$.

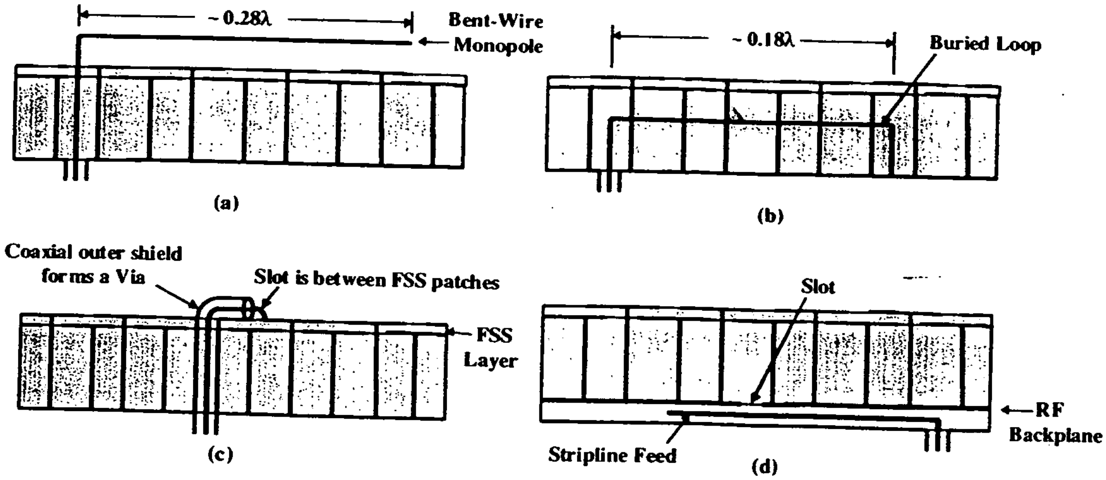
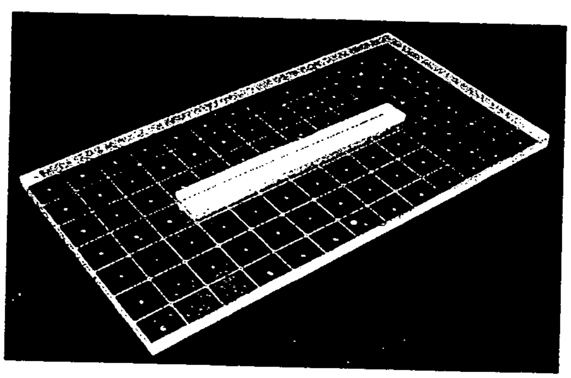


Figure H-17. Potential radiating elements for integration into AMC structures: (a) bent-wire monopole, (b) buried loop, (c) slot in the FSS, and (d) slot in the RF backplane.



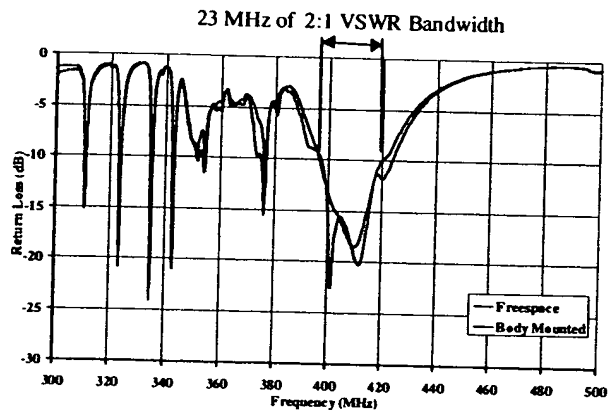


Figure H-18. A bent-wire monopole designed for UHF (385 MHz) has a total height of .75" (λ/40): (a) 8.6" x 16" ground plane, (b) measured return loss.

The buried loop element is particularly attractive since it does not protrude above the FSS surface, it is physically smaller than the bent-wire monopole, and it can be fabricated using low cost printed circuit technology. Figure H-19 shows a computer model for an L-band loop element of length 1.41" buried in an AMC of total height .070". A full-wave simulation of the return loss, shown in Figure H-20, predicts a -5 dB return loss bandwidth of 9%. This is extremely encouraging for such an electrically small element where Chu's formula ($Q=1/(ka)^3$) for the fundamental bandwidth limit of linearly polarized antennas yields an absolute maximum fractional bandwidth ($BW=2/Q$) of 30%, assuming the element is contained in a sphere of radius a=1.41"/2. It implies the buried loop is an efficient coupler to the AMC structure.

switch state has an 11% instantaneous VSWR bandwidth, then the operational bandwidth is $(1.11:1)^5$=1.68:1. A ratio of 1.7:1 is needed for elements in the demonstration array.

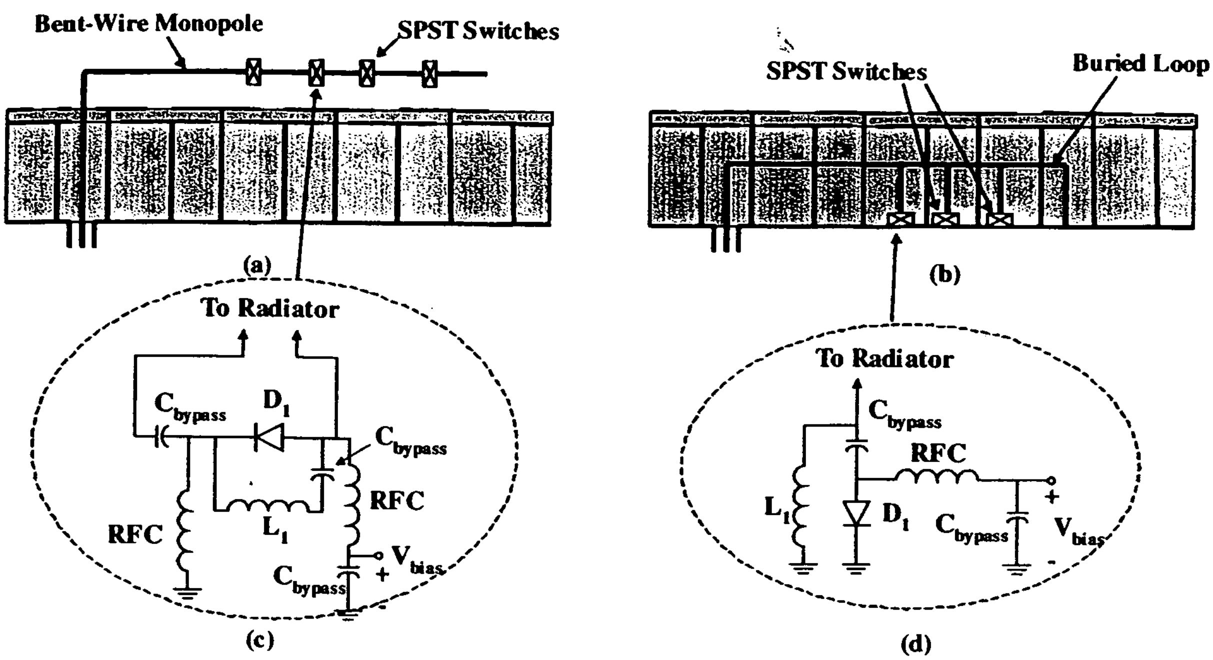


Figure H-21. Candidate reconfigurable elements suitable for integration into AMC structures.

The baseline switch technology will be PIN diodes. However, MEMs RF switches will also be evaluated for this function if available. A good candidate appears to be the thermally actuated, ohmic contact, MEMs relays now under development by MCMC [H4]. Their proposed package is a 70 mil high flatpack, which could easily be embedded in the RF backplane and controlled via stripline control lines in a manner similar to control lines shown in Figure H-8 or H-10.

One of the most significant merits of using a MEMs switch is to dramatically lower the OFF state parasitic capacitance relative to that of the PIN diodes. This will eliminate the parallel tuning inductors required with PIN switches (L_1 in Figures H-21(c) & (d)).

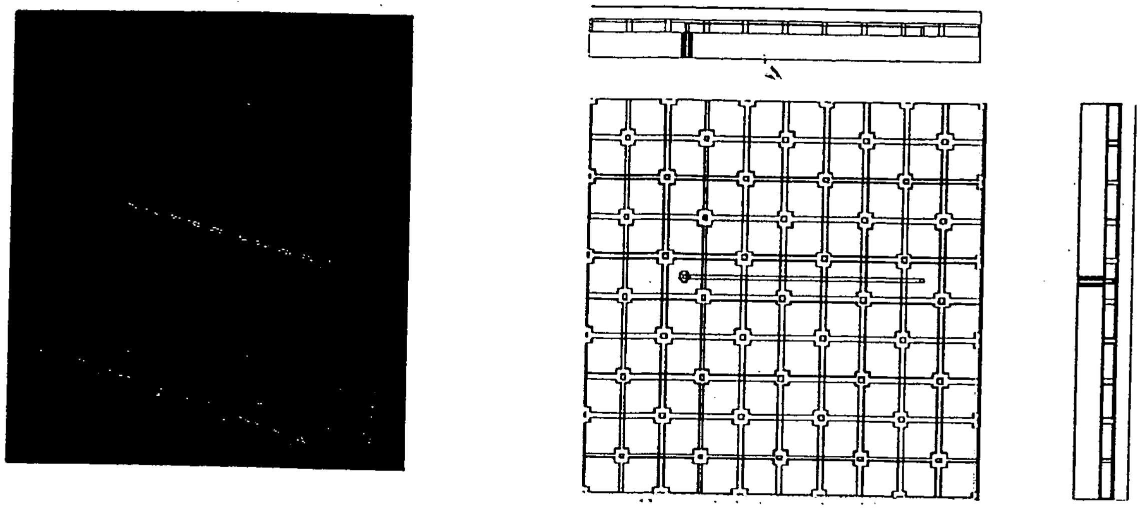


Figure H-19. Computer model of an L-band buried loop antenna element (Micro_stripes TLM simulation).

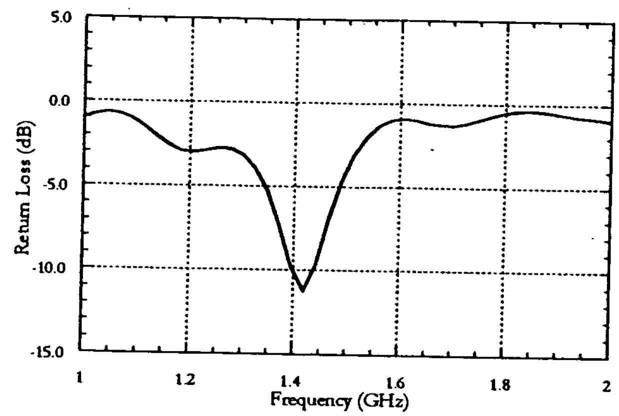


Figure H-20. Calculated return loss for the buried loop shown in Figure H-19 predicts a –5 dB return loss bandwidth of about 9%.

Our baseline approach for element reconfigurability is to insert SPST switches in series with the bent wire monopole. Laboratory experiments have shown that the length of bent-wire monopoles must be trimmed between 0.25λ to 0.3λ for the best VSWR bandwidth. A reconfigurable length monopole is shown below in Figure H-21(a) where the PIN diode switch circuit of Figure H-21(c) is used as a series SPST switch. An alternative reconfigurable element is the buried loop shown in Figure H-21(b) whose loop length is shortened through the use of grounded SPST PIN switches as shown in Figure H-21(d). The circuit in part (d) could also be used across a radiating slot (see Figure H-17(d)) to reconfigure the slot's effective electrical length.

What is the operational bandwidth that can be expected from a single reconfigurable element, assuming the AMC bandgap is sufficiently large and/or reconfigured? If we assume that the monopole or loop has four SPST switches for a total of five switch states, and that each